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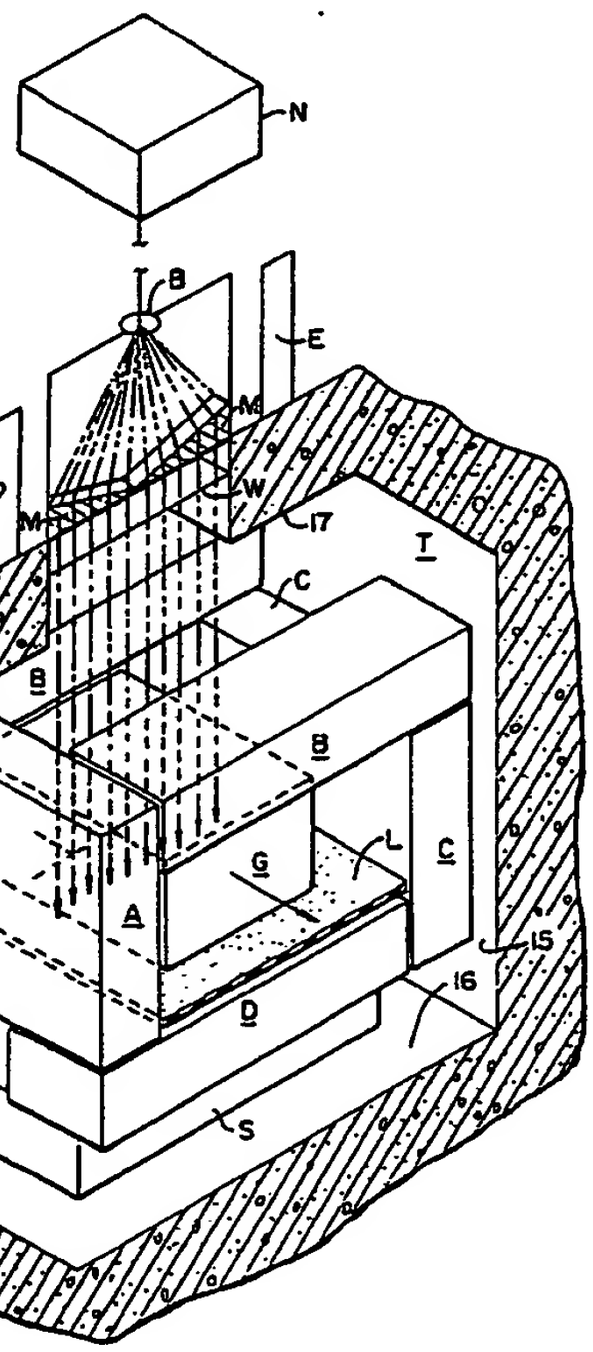
(54) Title: IMPROVED NITROGEN DETECTION

(57) Abstract

An apparatus and process for detecting concentrations of nitrogen such as explosives or narcotics, in suspect articles such as luggage (G). A racetrack microtron or linear accelerator (N) having an electron beam (B) at an energy level in the range of 50 MeV is electronically swept across a tungsten target (W) across the width of a suspect bag (G). The bag (G) is irradiated from the tungsten target (W) with x-radiation to produce the short lived isotope N^{12}. An array of scintillation detectors (A, B, C, D) observes gamma radiation of the 4.4 MeV level produced in the decay of the N^{12}. Two counts of the scintillation are taken; one for the entire observed half lives of decay (preferably 4) and the other for the ending half-life. This latter count is multiplied by four and subtracted and thereafter the remnant level observed. This latter count imparts to the test a high sensitivity enabling background levels of N^{13}, O^{15} and other short-lived positron emitting contaminants to be subtracted out of the count.



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IMPROVED NITROGEN DETECTION

This invention relates to an improved nitrogen detector and more particularly to an apparatus and process for screening suspect articles such as luggage for excess quantities of nitrogen, the excess nitrogen being possibly contained in explosives.

PRIOR ART

It has been proposed to tag all commercially produced explosives with a unique material that can be easily identified. Vapor taggants of considerable cleverness have been investigated. However, they have two strikes against them, namely the required cooperation of explosives manufacturers (common to any taggant program; explosives manufacturers are particularly resistant to introducing any substance that reduces the performance or reliability of the explosive), and the ease with which the system can be circumvented by appropriately sealing the bomb.

This second drawback can be circumvented if a taggant is used that can be detected by its nuclear properties, or by some other penetrating probe. I have previously suggested U.S. Patent 4,251,726 entitled "Deuterium Tagged Articles Such As Explosives And Method For Detection Thereof" issued February 17, 1981 that explosives or detonators that have been partially deuterated are easily detected by irradiation with 4 MeV gammas. This takes advantage of the fact that deuterium has the second lowest threshold for (gamma,n), and has the additional advantage that explosive performance is not sacrificed, since deuterated X has the same chemistry as ordinary X. The estimated cost is of the order of 10 cents per detonator or stick of dynamite. This scheme is adaptable to area searches (when everyone

has been evacuated), where, with the longer integration time permitted, it is possible to search a substantial fraction of an airplane at once. Unfortunately, all tagging schemes have the distinct disadvantage that they have no applicability to scenarios that are driven by forces of international terrorism.

With almost no exceptions, all explosives current in use contain large amounts of nitrogen, typically between 20% and 35% by weight. Although there are some common articles that also contain nitrogen (animal products and some synthetics), they generally have nitrogen present in lower concentrations and being generally more spread out.

A known method of nitrogen detection exploits the nuclear reaction produced by the capture of slow neutrons by nitrogen nuclei, giving off an unusually high energy (10.8 MeV) undelayed gamma ray that is easily detected by scintillation detectors. (One of the important improvements in the present invention, over the one just described, comes from the fact that the counting of gamma rays from the nitrogen isotope of interest can be done when the exciting radiation source has been turned off.) The parcel to be examined passes through a shielded enclosure in which it is subject to slow neutrons while being examined for gamma emission. In order to "see" whether the source of gamma rays is compact (a bomb) or spread out (a nylon sweater), a number of detectors are used to form a crude image of the gamma emitting object, i.e., the shape of the nitrogen-containing material. It must always be crude, since gamma ray detectors cannot be made with both good directivity and high sensitivity.

As additional related prior art, I discovered N^{12} and observed its then record-holding short half-life (12 ms) in about 1949. Nitrogen 12, Physical Review, 1949. The decay of this lightweight isotope is almost unique in that it emits alpha, beta and gamma

rays, with the beta rays carrying a positive sign (positrons), and the gamma rays coming in two quite distinct energies, arising from two quite different processes. As do all positron emitters, N^{12} gives off two oppositely directed gamma rays, with energies of 0.511 MeV, when the positron stops and annihilates in contact with an ordinary electron. The decaying N^{12} turns into C^{12}, 98% of the time in its ground state. But in 2% of the decays, the C^{12} is formed in an excited state, 4.4 MeV above the ground state, and that state immediately decays by the emission of a 4.4 MeV gamma ray, that exhibits the 11 millisecond half-life (present best value) of all the other decay products. So only one percent of the emitted gamma rays have the 4.4 MeV energy; the others have 0.511 MeV of energy.

The reaction $^{14}N(gamma, 2n)^{12}N$ was seen by Panofsky et al. in about 1952. This reaction has received little, if any, attention since its discovery, to the point that in a careful search of tabulations of nuclear reactions, I did not find any reference to this reaction. (I learned of it only recently, in a private conversation with Dr. Panofsky, when I told him I was sure it would occur, and wondered what its cross-section might be. It was at that time that he referred me to his 1952 article in Physical Review.)

RELATED DISCLOSURE
(NOT PRIOR ART)

A method and apparatus for detecting concentrations of nitrogen between 20% and 30% by weight such as is common in explosives is disclosed. An electron accelerator having an output electron beam at a level of about 50 MeV is targeted onto a typically tungsten target to provide gamma radiation levels. Deflection magnets adjacent to the target deflect the electron beam of the accelerator to cause it to scan. Articles placed on a conveyor containing suspect nitrogen are

systematically scanned and output gamma radiation of 4.4 MeV detected from nitrogen 12. Nitrogen concentrations and consequently expected concealed explosives are easily mapped in two or three dimensions, quantitatively. See Patent Application entitled "Nitrogen Detection" filed October 9, 1985 as Serial No. 06/847,191.

SUMMARY OF THE INVENTION

An apparatus and process for detecting concentrations of nitrogen in articles such as luggage, is disclosed. The parameters of detection are designed to prevent concealed explosives from escaping detection. In its simplest form, and directed to baggage search, an accelerator having an electron beam with an energy of approximately 50 MeV is electronically swept across a tungsten target at 2½-inch wide intervals across the width of a suspect bag passing at a rate of approximately 6 inches per second. I consider the "standard bag," 32 inches long, 24 inches high, and 16 inches wide, lying on its side on a movable belt. A square section volume the depth of the bag is irradiated downward from the tungsten target with high energy x-rays to produce among other things the short-lived isotope N^{12} (11 millisecond half-life is the present "best value"). A large scintillation detector having a fractional solid angle of as much as 80% to 90% of the maximum possible observes and counts the 4.4 MeV gamma rays from the decay of N^{12}. A computer memory with about 130 storage registers accumulates counts, with the number in each register being proportional to the number of grams of nitrogen beneath the corresponding 2½-inch square pixel on the large surface of the bag. At the "slow belt rate" of 6 inches per second, the 32 inch bag passes the x-ray beam in 5.3 seconds, so each pixel is examined for 5.3/130 = 0.041 seconds, or nearly 4 half lives of N^{12}. So the number of 4.4 MeV gamma ray counts is proportional to the number of grams of nitrogen in the 2.5-inch square

pixel. To a good approximation, only nitrogen can give rise to counts "in the 4.4 MeV window," but methods of cancelling any possible interferences by non-nitrogenous materials will be discussed.

A tunnel constructed for the detector is disclosed which includes a mineral oil "backstop" for the bombarding high energy x-radiation and a boron glass plus lead lining to inhibit slow neutrons and gamma rays from escaping the testing chamber. A technique for atmospheric flushing of the bag is disclosed where the sensitivity of the test must exceed the level of atmospheric nitrogen background.

OTHER OBJECTS AND ADVANTAGES

An object of this invention is to disclose an improved apparatus and technology for use in detecting the presence of nitrogen in containers such as baggage. It operates by observing the decay of N^{12}, and discriminating the N^{12} out on the basis of its unique delayed gamma ray energy of 4.4 MeV, with a back-up related to its uniquely short half-life of 11 milliseconds. In an earlier technique, one observes prompt gamma rays with energies in the 10.7 MeV range, but such high energy gamma rays are not seen in radioactive decay. Examination of the isotope table shows that hardly any interfering gamma rays in the 4.4 MeV range are known, so the detection of such a delayed gamma ray is convincing proof that N^{12} has been detected, even without noting its 11 millisecond half-life; when that short life is observed, the proof can be made beyond doubt.

The surprising feature of the present invention is that I have found that I can build the most useful nitrogen detector by ignoring the very intense annihilation radiation (200% per decay), and concentrating on the 4.4 MeV gamma ray (2% per decay). This is even more surprising when one realizes that the two annihilation quanta have a unique feature (colinearity,

back-to-back), that offers a number of advantages when searching baggage for high explosives. So I am giving up three obvious advantages that derive from the use of the very abundant annihilation radiation, (1) increased intensity, by a factor of 100, (2) colinearity, which could be used to pinpoint the location of the stopped positron, and (3) the use of two coincident pulses to eliminate the troublesome "shot noise" from a photomultiplier tube used at high sensitivity.

It will be apparent to those skilled in the art that when I give up these important features of the N^{12} signature, I must get something important in return. And that is the freedom from interference by short-lived positron emitters, most of which can be made by the more prolific (γ,n) reactions on elements such as Mg, Al, Si, S, Cl, K, and Ca, all common enough to be found in baggage. A search of all entries in the Table of Radioactive Isotopes, John Wiley & Sons, 1986, has turned up a few gamma ray emitters in the 4.4 MeV range, but out of a total of 20,000 tabulated gamma ray energies, that is a very small fraction, and fortunately none of those radioactive isotopes will interfere with the detection of nitrogen in baggage. First of all, almost all radioactive gamma rays have energies below 1 MeV, and a very few are in the 1 to 4 MeV range. Almost none have energies above 4 MeV, and the following list tabulates all that are of interest--but of no concern to this proposed search technique.

(1) Be^{11}, half-life 13.6 seconds has a 4.67 MeV gamma ray, with a 2.1% branching ratio, and it can be made from B^{11}, in an (n,p) reaction. So the boron I have suggested might line the tunnel must be kept at some distance from the detector. So Be^{11} will not cause any problems; boron is not a frequent constituent of baggage, and because of the 13.6 second half-life any Be^{11} counts would be of low intensity and appear to

be spread uniformly throughout the bag, and would not pass the test for very short half lives.

(2) Ca^{38} has a 0.44 sec half-life, and a 3.2 MeV gamma ray, at 0.29% branching ratio. Even without good gamma ray energy resolution, Ca^{38} should cause no trouble because its half-life is 40 times greater, giving us two factors in favor of N^{12}, 40 x 14, with another factor of 2%/0.29% = 7. So, without good gamma ray energy resolution, N^{12} should give about 4000 times as many useful counts per gram as Ca^{38}.

K^{37} should give even less of a problem than Ca^{38}. Its half-life is 1.23 sec, its gamma ray energy is 3.6 MeV, but its branching ratio is only .014%. (The second time-dependent factor will be explained later.) (Both Ca^{38} and K^{37} are made in the (γ,2n) process, so their production cross-sections will be substantially less than the ones made in the (γ,n) reactions, that are eliminated by ignoring the annihilation radiation.)

(3) Cl^{32}, Al^{24} and P^{28} are all made by the (γ,3n) reaction, with high threshold energies, longer half lives and small cross-sections, so they will cause no problems.

(4) O^{13} is also made in a (γ,3n) reaction, has a half-life of 8.9 milliseconds, and emits the same 4.4 MeV gamma ray as does N^{12}. So the only property of O^{13} that keeps it from ruining the detection scheme outlined here is that the threshold energy for making O^{13} from O^{16} is 52 MeV, which is higher than the energy available in the suggested 50 MeV x-ray beam. (The x-ray energy can probably be increased to 60 MeV without encountering enough O^{13} to cause trouble, because (γ,3n) cross-sections start up slowly above their energetic thresholds.)

There is a possibility that N^{16}, formed by fast neutrons on oxygen could give rise to some counts in the "4.4 MeV window," but a method of automatically

subtracting such counts out of the storage registers will now be described.

The 7 second half-life N^{16} is a unique radioactive substance in that it emits both high energy negative beta rays, with a maximum energy of 10.4 MeV, together with two of the highest energy radioactive gamma rays known--6.1 and 7.1 MeV. There is little chance that these high energy gamma rays could be mistaken for the 4.4 MeV gamma rays from N^{12}, but it is easy and valuable to count them in "their own energy window." There are two minor ways in which the decay of N^{16} might give an occasional count "in the 4.4 MeV energy window," and so gave a fake indication that such a count signalled the presence of nitrogen, rather than oxygen, from which the N^{16} was formed. The first way involves the production of bremsstrahling, or continuous x-rays (by the same process used to generate the 50 MeV x-rays--fast electrons "shake-off" photons when they are scattered by nuclei). The production of such x-rays varies directly with the Z of the "target," which is why we use tungsten when we want the most x-rays possible. So the production of bremsstrahling is first of all down by a factor of 10, the ratio of the atomic numbers of tungsten and oxygen, and secondly, it is down by another factor of ten or more, because x-ray photons of all energies comprise the bremsstrahling, rather than the narrow 4.4 line from N^{12}. (A bremsstrahling photon with an energy of 4.4 MeV is identical to the desired photons from N^{12}, so it will be counted in the large scintillation detector.)

Another way that N^{16} could give some light flashes in the large scintillator is by being made <u>inside</u> the scintillator, by neutrons interacting with some oxygen atoms that may be required to be present to make the scintillator operate properly. We will do our best to minimize the presence of oxygen in the plastic scintillator, but some small amount may be necessary.

One normally adds a fluorescent material (fluor) to an organic solvent, such as Xylene or mineral oil. (I will treat the solid organic scintillator in this discussion of the way organic scintillators work, as though it were a liquid because I don't know the proper words to describe the manufacture of solid scintillators; it may be a trade secret, but certainly the basic physics of liquid and solid organic scintillators is the same, in that only small amounts of active scintillating material must be mixed into the inert energy absorbing material.) The solvent molecules are excited by collisions with the fast electrons or positrons released by the action of the gamma rays. The excitation lives long enough in the solvent molecules so that they can transfer their energy to the fluor molecules, in subsequent collisions, and that molecular-transferred energy gives rise to the optical photons that are eventually detected by the photomultipliers. It is for this reason that we can make a satisfactory organic scintillator when only a few percent of the molecules present have any fluorescent properties. (The bulk of the liquid is an inexpensive organic solvent.) A typical fluor in use with a Xylene solvent is diphenyloxazole, which has a molecular weight of 220, with only one oxygen atom in its molecule. So the fraction of the molecule that is oxygen, by weight, is 16/220 = 7%. When we multiply this small fraction by the fluor to solvent ration, we see that the chance of making N^{16} is very small, and since its half-life is 700 times greater than that of N^{12}, the initial counting rate is 700 times smaller, for the same number of radioactive atoms produced. And as I will soon show, by the use of a "real time subtraction technique," the numbers of recorded counts will be still further reduced. And as I said earlier, gamma rays from N^{16} should not cause problems, and the only other way N^{16} counts can be detected are those made inside the scintillator, and from positrons in the energy range from 3 MeV to 3.8 MeV (400 keV on either side of

the desired "line" from N^{12} gamma rays). And those counted positrons are only a very small fraction of the continuous positron spectrum from N^{16}. As will be explained later, we typically lose 1.022 MeV in recorded gamma ray energy by not absorbing the two annihilation gamma rays from the positron made in the "pair-production" absorption of the 4.4 MeV gamma ray. And as I mentioned, those beta ray counts can be eliminated by two separate tests, (1) they don't appear as a "line" at 3.4 MeV, and (2) they have a half-life 700 times too long.

Another remote possibility of making N^{16} from the oxygen in the liquid is by x-ray interactions with the very rare heavy isotopes of oxygen, for example $O^{17}(\gamma,p)N^{16}$, or $O^{18}(\gamma,d)N^{16}$. I mention these very improbably reactions to indicate how thoroughly I have searched to find reactions that might interfere with the detection of nitrogen. (Oxygen plus high energy x-rays can produce true N^{12}, by improbable reactions such as $O^{16}(\gamma,n+H^3)N^{12}$, and $O^{16}(\gamma,2n+d)N^{12}$, but it is doubtful that such reactions will contribute appreciably to the total count of 4.4 MeV gamma rays.)

The foregoing analysis gives me confidence that the proposed nitrogen detector will respond only to nitrogen, and will yield no appreciable number of false counts due to other elements.

A further object of this invention is to disclose an improved detection apparatus. According to this aspect, a tunnel, preferably in the ground, is irradiated from overhead through the bag on its transporting belt and onto an oil backstop. A large organic scintillator composed of individual elements A, B, C, D is placed around the suspect luggage G. Scintillator elements B and D are divided so as to define a gap permitting the X-ray beam and interval in which to pass. The remaining scattered produced radiation (gamma rays and slow neutrons) impacts peripheral boron glass plus

lead walls lining the tunnel. Luggage passing at the rate of 6 inches per second can be automatically screened for contained explosives.

An advantage of the disclosed tunnel construction is that it may be easily assembled in most airports at a ground-level facility.

Yet another advantage of the disclosed system is that low levels of radioactivity only are created; the system may be repaired after relatively short periods for shutdown. One option is to have a single accelerator whose beam can be switched between two neighboring tunnels, so that the second tunnel, with its belt and scintillation detector could be used while the residual radioactivity in the first tunnel was decaying to a level acceptable to a repair crew.

Yet another object of this invention is to disclose a system of flushing background atmospheric nitrogen from luggage. According to this aspect the atmospheric pressure in luggage is cycled three times to a level of approximately 1/2 an atmosphere. In repressurizing, the luggage is exposed to a carbon dioxide atmosphere. There results a flushing of all but 1/10 of the atmospheric nitrogen from the bag. I do not believe that this flushing operation will ever be needed, but it is good to know that it is easy to accomplish.

An additional advantage of this disclosed invention is that it is capable of locating narcotics check in inspected articles such as baggage, where the narcotics have a nitrogen content in excess of 3% by weight.

BRIEF DESCRIPTION OF THE FIGURES

Other objects, features and advantages of this invention will become more apparent after referring to the following specification and features in which:

Fig. 1 is a perspective partially broken away view of a tunnel illustrating a racetrack microtron or

linear accelerator bombarding a suspect bag passing on a transporting belt with a surrounding scintillation detector;

Fig. 2 is a graphic plot illustrating a technique for eliminating undesired half-life counts in real time;

Fig. 3A is a perspective view of one of the detector elements A, B, C, or D illustrating a preferred construction of one of the detector elements; and

Fig. 3B is a detail of the detector of Fig. 3A.

DETAILED DESCRIPTION OF THE FIGURES

Fig. 1 shows a perspective view of the apparatus of this invention. The invention is preferably installed in a tunnel T in the ground. Tunnel T is defined by walls 14, 15, 16, and 17.

A bag G is placed on a conveyer L. The conveyor L moves a passing series of such bags through an X-ray beam and an array of scintillation detectors A, B, C, and D. A typical detector element will later be described with respect to Figs. 3A and 3B. It will be understood that all of the elements A, B, C, and D have the interior construction set forth in Figs. 3A and 3B.

An electron beam B originates at a linear accelerator N. An electromagnet schematically shown at E on both sides of the electron beam B, electronically scans the electron beam. The beam B, after scanning, then enters a magnetic lens M. The beam is bent at steady lens M and then becomes incident directly downward upon a tungsten target W in about 10 equally spaced spots with a spatial separation of about 2.5 inches. 50 MeV X-rays are produced in the target W, and directed in narrow bundles vertically downward.

It will be observed that detector B is divided into two portions overlying the conveyor L to allow downward passage of the beam. Likewise detector D is

divided into two portions to allow downward passage of the beam. The downward passage of the beam continues until the beam is absorbed at a full oil tank S.

The reader will understand that just because the detector elements B and D are divided into two sections each, the representative construction remains the same. That is to say, each detector section B and D is constructed exactly like the representative construction illustrated in Figs. 3A and 3B.

Insulation is required in tunnel T against scattered x-rays, neutrons, and radioactive gamma rays. The tunnel has a cross-section of about 5 feet by 5 feet, and the walls 14, 15, 16, 17 are, for the most part, lined with layers of, or mixtures of sulfur, boron oxide, and lead. These elements have good properties, insofar as freedom from long-lived gamma ray emitters are concerned, so workers can enter the tunnel safely in about a day. Long-lived beta ray emission can be stopped by covering the tunnel wall with plywood or sheets of aluminum. In addition, boron absorbs neutrons, so very few neutrons or high energy photons will leak out of the open ends of the tunnel.

Regarding such escaping radiation, the use of the equivalent of a revolving door, to keep neutrons and gamma rays from escaping out the ends of the tunnel may be installed if imposed radiation limits so require. See my U.S. Patent No. 4,251,726 issued February 17, 1981. Composition of the wall material may be determined by the routineer with reference to the Table of Radioactive Isotopes. For example, various kinds of sulfur linings may be used.

An oil backstop S is provided. I use the electron beam from a 50 MeV electron accelerator. It makes x-rays with energies up to a maximum of 50 MeV.

X-rays impacting nitrogen (N^{14}) produce, by the (γ,2n) reaction, an 11 millisecond half-life emitter of 4.4 MeV gamma radiation, plus copious amounts of

annihilation radiation, with an energy of 0.511 MeV, which the detector is designed to ignore. The 4.4 MeV γ-rays are picked up by the detector.

Fig. 1 shows that oil is used as part of the tunnel wall only where it can be struck by the x-rays coming directly from the tungsten target. The reason is that high energy x-rays striking Carbon can make Be^7, 53-day half-life emitter of 0.477 MeV gamma rays, which are difficult to shield. By using oil, instead of some solid material, we can drain the oil into a sump, where it poses no radiological hazard to workers in the tunnel. Neutrons and x-rays behave quite differently when scattered by potential wall materials. Any high energy x-ray photon loses energy in a very drastic manner, as it scatters from any element--the scattering is done by the electrons, which are present in all materials. For example, a 50 MeV photon ends up with the following energy, when scattered through these small angles: 10° - 20.2 MeV, 20° - 7.3 MeV, 30° - 3.6 MeV, and for larger angles, 90° - 0.5 MeV, and 180°, 0.25 MeV.

We will get a big flash of light in the counter when the scattered x-rays hit, but they will leave no appreciable amounts of radioactivity that can be detected by the scintillation detector; it is not sensitive to the annihilation radiation from the 20 minute C^{11}, or to the low energy positrons from the C^{11}. So although the scintillation detector would be considered to be radioactive, by most measures, that radioactivity will not be recorded in the detector described herein. Due to the intense flash of light when the x-rays are "on", we will want to turn off the high voltage on the photomultipliers to protect them at that time, so they will be ready to look into the liquid, during the next 44 milliseconds, before the x-rays are turned on again in a short burst.

The light from the accelerator burst will, for all practical purposes, be gone before we want to start looking for N^{12}, in a few milliseconds. The proper delay time is of the order of milliseconds, to be determined by experiment. Slow neutrons "bouncing around" in the tunnel can last for a time given by $\Delta t=L/v$, when v is the velocity of a thermal neutron (2200 meters per second), and L is the travel distance in meters. So, if L = 2 meters, Δt=1 millisecond. The boron lining of the tunnel will decrease the "lifetime" of the bouncing thermal neutrons inside the tunnel, and permit the counting of the N^{12} gamma rays to start earlier than would otherwise be the case. It might also help to narrow the cross-section of the tunnel on either side of the detector.

This delayed counting feature of the N^{12} method makes it much improved over the earlier techniques, that look for a "signal," while the activating radiation is still "on" (such as the use of thermal neutron bombardment; to find the high energy gamma rays emitted by nitrogen when it captures slow neutrons, one must find those high energy gamma rays in the huge background of 2.2 MeV gamma rays, due to the capture of slow neutrons on the ubiquitous hydrogen).

The oil backstop can generate C^{11} (20 minute half-life), which we do not detect, and high energy neutrons. In order to diminish the number of neutrons in the vicinity of the scintillation counter, and the N^{16} that those neutrons can produce on O^{16}, by the (n,p) reaction, it may be desirable to put the oil backstop at the bottom of a narrow well, down which the high energy x-rays can pass, but which will impede the upward flow of neutrons.

The tunnel T must be suitably lined to prevent escape of neutrons. Neutrons scatter quite differently, and more like hard spheres. So if they bounce off heavy nuclei (they hardly interact with electrons) they can

keep most of their energy, even when turned through 180°. But frequently, when high energy neutrons scatter from nuclei, they lose appreciable amounts of energy, by the process called "inelastic scattering." The energy loss of the neutron appears as gamma radiation from the struck nucleus. But neutrons with more moderate energies are heavily absorbed in boron. Therefore, the tunnel is lined with boron (perhaps B_2O_3--a glass-like material) plus lead. It may be found that no appreciable harmful radiation leaks out the ends of the tunnel, particularly if the tunnel has curves in it to prevent neutrons that are scattered only once from leaking out, so the bags may not need a "radiation tight door."

Optionally, such a door could open and close, to let in the bags, so long as the accelerator was turned off whenever the door was open. This expedient will depend upon determined and imposed radiation limits.

The detection physics of this disclosure may be summarized as follows: I make use of the fact that N^{12} has by far the shortest lifetime one can make with 50 MeV x-rays, and that emits gamma rays in the 4.4 MeV range. Every time a burst of x-rays irradiates a passing bag G, we make N_i radioactive atoms of the ith element. We can think of the irradiated volume of the bag as being 2.5" x 2.5" x 16" = 100 cubic inches. If this volume contains m_i grams of the ith element, with an atomic weight A_i, then it contains m_i/A_i moles of that element.

Each mole contains 6×10^{23} atoms, so the small volume contains 6×10^{23} m_i/A_i atoms of the ith element. Each atom has an "effective cross-section," σ_i, for the reaction of interest. We are exploring this volume along the 16-inch axis, so the area we see is 2.5" x 2.5" = 40.32 cm^2 = a. If we shoot in particles at random along the 16-inch axis, the chance that one will produce the reaction of interest is a probability equal to the effective area of all the atoms of

interest, $(6 \times 10^{23} m_i/A_i) \times \sigma_i$, divided by the area of the volume, a = 40.32 cm^2.

In the following calculation, the reader will note I use numbers now known only to an order of magnitude, but that is of no concern, since we can always make more "signal," by using more x-rays. The problem is therefore not signal, but signal-to-noise ratios and the foregoing analysis has shown that the interfering "noise" will most probably be negligibly small. Assume that we have a layer of explosives 1-inch thick, parallel to the belt, and perpendicular to the x-ray beam. If we assume the density of the explosive to be 1 gm per cm^3, and 30% by weight nitrogen, then there will be a surface density of nitrogen equal to S.D. = 2.54 (cm thick) x 0.30 (gms/cm^3) = 0.76 gms/cm^2. Since the atomic weight of nitrogen = 14, there will be 0.76/14 = 0.0544 moles of N per cm^2 = 3.27×10^{22} atoms of N per cm^2. If we assume the cross-section for the (γ,2n) reaction to be 10^{-28} cm^2 (10^{-4} barns, where 1 barn = 10^{-24} cm^2), the probability that any incident photon will produce the desired reaction is $3.27 \times 10^{22} \times 10^{-28} = 3.27 \times 10^{-6}$. That is a very small chance, but we can shoot in lots of high energy photons, so we can still make many N^{12} atoms.

Again, for an order of magnitude estimate, assume we have a beam of 50 MeV electrons (from our accelerator) with a beam current of 10 milliamps (6×10^{16} electrons per second), for 2 microseconds. This is a peak power of 500 kW, which is a "reasonable" power from an inexpensive electron accelerator of the "race-track microtron" variety, and also from a more conventional linear accelerator. So 1.2×10^{11} electrons hit the tungsten target in that short interval of time. About 80% of the electrons make photons, so we make 10^{11} photons per pulse. Of these, about 22% have energies high enough to make the (γ,2n) reaction go. (I assume the maximum energy is 50 MeV, and the threshold

energy is 32 MeV, so the useful fraction is close to In 50 - In 32 =0.45 [In is the natural log]). So the useful number of photons per burst (to order of magnitude) is 4.5×10^{10}. Now, to find the number of N^{12} atoms made per burst, we multiply 4.5×10^{10} by the probability, 3.27×10^{-6}, to give 1.5×10^{5}. Thus, sufficient reaction is present to enable detection, at each pixel, even though only 2% of the N^{12} atoms emit 4.4 MeV gamma rays.

We can see that this 2.5-inch pixel scan looked at only 6.25 cm^2 x 2.54 cm x 1 grams of explosive = 15.9 gms of explosive. This is 0.57 ounce. Known specifications ask for the detection of either 2.5 or 4 pounds of explosives. We will probably count about 0.5% of all the N^{12} atoms we make, or $1.5\ 10^{5} \times 5 \times 10^{-3}$ = 750 per 0.57 oz, or $2./1 \times 10^{4}$ counts per pound, or 53,000 counts per 2.5 lbs of explosives. (That is a satisfactory high total count, in a situation where I have not been able to identify an interfering reaction.)

I now will consider the amount of nitrogen in the air in the bag. The density of nitrogen in air is close to 10^{-3} gms/cm^3, so the surface density of nitrogen in a 16-inch thick bag is $16 \times 2.54 \times 10^{-3}$ = 0.04 gms/cm^2. Compare this with the surface density of our 1 inch of explosive, which we have seen is 0.76 gm/cm^2, or 19 times less. But the air N^{12} is a fairly constant background, whereas the explosives N^{12} varies from place to place, with very different values in neighboring pixels.

A worst case scenario constitutes bag G constructed of sheet explosives. The area is then 32" x 24" x $(2.54)^2$ = 5000 cm^2. If we want to hide 4 lb of explosives in this way (about 2000 gms), the surface density of the explosives is about 0.4 gm/cm^2, so the thickness of the plastic is less than 2 mm, and the surface density of nitrogen is 0.4/3 = 0.13 gms/cm^2.

This is more than 3 times the air density. It may also true that such a thin sheet of xplosive will not be able to sustain a detonation wave.

If atmospheric nitrogen ever presents a significantly interfering fraction of the detected reaction, the bags can be passed through a moderate vacuum chamber, and the nitrogen exchanged with CO_2, or some other inexpensive, undetectable gas. Bags do let the air escape, as the outside pressure is reduced.

Continuing with the worst case scenario of sheet explosive, it is useful to calculate the thickness of the explosive that could be made to look like a more ordinary bag cover. I assumed the mass to be 2000 grams, so with a total bag area of 2 x 24" x 32" + 2(24" + 32") x 16" = 3,328 in^2 = 21,400 cm^2, so, at unit density, the thickness of the bag forming surface is (2000 gm/1 gm/cm^3)/21,400 cm^2 = 1.0 mm!

At one time, I incorrectly concluded that a bag made of sheet explosive had a surface density of nitrogen smaller than that of air, so I looked into the possibility of flushing the nitrogen out of the bag. That is a straightforward engineering job, using standard "roughing pumps" and gas valves. Flushing bags from sea level to 8000 ft and back to sea level with CO_2 takes 7.65 flushes to get the atmospheric nitrogen down to one-tenth of its sea level value with replacement by CO_2. Each flush leaves 0.74 of the previous density of nitrogen. So to get down to 0.1 of sea level nitrogen pressure, we want $0.74^n = 0.1$, or n log 0.74 = log 0.1, so n = 7.65.

If we flush the bags up to 20,000 feet, $e^{-20/26} = 0.46$, the number of flushes to get down to $p = 0.1p_o$ is given by n log 0.46 = log 0.1, so n = 3.0. That is preferred. (The air is pumped down at each of the three cycles to just under half of normal pressure--0.46.)

So now, each 16-inch thickness contains atmospheric nitrogen with a surface density of 16 x 2.54 x

$10^{-3} \times 10^{-1}$ = 4.1 milligrams p r cm². The question now is can the expedient of flushing be avoided?

A list of some of the nitrogen surface densities expected can be instructive. (Assumed explosive density = 1 gm/cm³).

1 inch of normal explosive	762 mg/cm²
1/4 inch of normal explosive	190 mg/cm²
Sea level air	41 mg/cm²
Sea level air flushed three times with CO_2	4 mg/cm²
1 mm thick explosive as bag wall	100 mg/cm²

From a review of the above densities, we can easily see the exceedingly thin explosive, since it would raise the detected N at every point in the bag, from its normal value of 41 mg/cm² to the new value of 100 mg/cm² everywhere. I am confident that this big factor of 100/41 = 2.5 in almost every one of the 130 pixels, or, at twice the resolution, 520 pixels, could not escape detection.

For purposes of this disclosure radioactivity can be analyzed in either of two ways: 1) the number of active atoms in the sample at any time; or, 2) the number of atoms that decay (emit positrons and annihilation gamma rays) per second. (The number of atoms that decay per second by emitting 4.4 MeV gamma rays is 2% of the number that decay by emitting positrons.) These two measures of radioactivity are always proportional to each other; if we call 1) N (not to be confused with nitrogen, but) meaning the total number of radioactive atoms in the sample--in our case, the sample is a volume element 2.5" x 2.5" x 16". The decay rate is called dN/dt, and it is equal to 0.693 $N/t_{\frac{1}{2}}$, where $t_{\frac{1}{2}}$ is the half-life, or, for N^{12}, 0.011 seconds. (0.693 is ln 2, and a constant that all nuclear physicists know.) So if we have made the calculated 150,000 N^{12} atoms in our elongated box, they will decay, initially,

at the rate of 0.693 x 150,000/0.011 = 9.5 x 10^6 per second. (If they continued to decay at that rate, they'd all be gone in t = N/dN/dt = 1.5 x 10^5/9.5 x 10^6 = 0.016 second, which is one half-life divided by 0.693. Everyone knows that they don't keep decaying at that same rate; as the earlier ones decay, that leaves fewer in the sample, so N decreases with time; and, consequently, dN/dt decays in the same way, since dN/dt is proportional to N, through the time constant, 0.016 seconds. The fraction of atoms left after m half lives is $(0.5)^m$, so if we do roughly as I plan, we'll count for about 4 half lives. If there were 1.5 x 10^5 N^{12} atoms in the box, and we detected the 4.4 MeV gamma rays with an efficiency, f, of 0.5%, we would have 1/8 of the original number after 3 half lives, and 1/16 (= 0.063) after 4 half lives. So out of 150,000 atoms and after 4 half lives, we would have detected 1.5 x (1 - .063)10^5 x 5 x 10^{-3} = 703 N^{12} atoms. This number is slightly smaller than the number of 750 calculated earlier, because we stopped counting at the end of 4 half lives, and so missed 47 counts. (We will see later that those counts, which signal the presence of nitrogen in the bag are not lost, but simply assigned to a "later pixel.") To put things in proper perspective, we should remember that we have been discussing the detection of a 1-inch thick layer of explosive covering a square 2.5 inches on a side. This is 3.66 ounces of explosive, at unit density. So, we detect 750 counts per 3.66 oz., or 3,280 per pound, or 10^4 for the required 3 pounds per bag ("mean" of 2.5 and 4 lbs, the two values specified by the FAA). The standard deviation of 10^4 counts is 102 counts, or 1%. It is now instructive to list the total number of counts for various items that might be found in a standard bag.

Object	Wt. lbs	Lbs. of N	Total Counts
Explosive	3	0.9	10,000
Air	0.56	0.45	5,000
Sweaters			
Orlon	0.81	0.214	2,380
Nylon	0.55	0.055	611
Wool (Large)	1.90	0.304	3,380
Wool (Medium)	1.31	0.210	2,330

A first glance at this table might make it look as though ordinary items might cause the detector to signal a false alarm. But on second thought, one must remember that the air count will be nearly the same for each of the 130 pixels, or 5000/130 = 38 ± 6 counts per pixel. The sweaters will give similar counts, since they are spread over many pixels. But compare these numbers with 3 pounds of explosive spread out over 13 pixels (1-inch thick bundle); the counts per pixel are therefore $10^4/13 = 751 \pm 27$. (If the bundle is 2 inches thick, the count per pixel will of course be 1500.) So, the explosive should stand out clearly for two reasons: (1) the number of counts per pixel is about twenty times larger than the background rate from air, and perhaps ten times larger than from the air plus a sweater, and (2) the high count per pixel will be seen for 13 or more neighboring pixels. One will not have to build much artificial intelligence into the controlling computer, to make it sound the alarm. I would suggest that bags which are not given an obvious "free of excess nitrogen" opinion, be automatically sent through an ordinary x-ray scanner, to let a human operator search the bag for detonating equipment--wires and detonating caps.

Calculation can be made to show that the disclosed rate of scan just said fits with all the numbers in the problem. Assume the bags are spaced, center to center, by 36 inches, so their speed is 36"/6 sec = 6" per second. Each "look" at the N^{12} takes 4 half lives

(decay down to $\frac{1}{2}^4$ = 1/16 = 6%). The half-life is 11 milliseconds = 0.011 sec, so each "look" takes 0.044 sec. The time for a 32-inch bag to pass the scanning x-ray beam (it scans as a pencil beam, transverse to the belt direction--the 24-inch direction) in a time t = 32"/6" per sec = 5.33 sec. So the number of looks per bag is 5.33 sec/0.044 sec = 121. The area of the 32" x 24" face of the bag is 768 in^2. So the area of each pixel is 768/121 = 6.35 in^2. So as a first approximation, each square pixel should be $\sqrt{6.35}$ = 2.52 inches on a side. That would give 24"/2.52" = 9.52 columns by 32"/2.52" = 12.70 rows, for a total of 9.52 x 12.70 = 121.

For the purposes of the design, I round the numbers up changing 9.52 to 10, and changing 12.70 to 13. So the total number of pixels is now 10 x 13 = 130, and the time per pixel is reduced from 0.044 sec to 0.044 x 121/130 = 0.041. If we make the pixels square, with 2.5 inches on a side, we will scan 10 x 2.5" = 25" along the 24-inch direction, and 13 x 2.5" = 32.5" along the 32-inch (belt) direction. These are good numbers, but ones which can be further changed in the design to be sure that the complete surface of the bag is scanned. (It must be remembered as a worst case that a bomber might make the suitcase out of sheet explosive, to pretend that it was leather.) So we want the detector to come up with a number that tells quite accurately how many pounds of nitrogen the whole bag contains--including the walls and the air. (The total number of counts of 4.4 MeV gamma rays is directly proportional to the total amount of nitrogen in the bag.)

An alternate calculation on the scan rate can be made: the bag moves 6 inches per second, and the time per look is 0.041 sec, which is very close to the 4 half lives I've assumed earlier. We take 10 looks along the 24-inch direction, for each 2.5-inch step in the 32-inch direction. 10 looks takes 0.41 seconds, during which time the bag moves on the belt by (6 inches

per sec) x 0.41 sec = 2.46", which is close to 2.5", to show that the basic numbers are solidly based.

It has now been shown in broad outline how the generation of N^{12} in baggage, under x-ray bombardment can form the basis for an explosives detection device. It has the good feature that it should not ever let through a bag that has a few pounds of explosives in it. (So the detection efficiency should be very nearly 100%.) And since I can't find, in a library search, any source of interfering 4.4 MeV gamma rays, I will say that the number of "false positives" should be close to zero.

I will now suggest two other ways of operating the proposed nitrogen detector. Up to this point, I have considered using the four half lives per pixel scan, to "observe" the decay of the N^{12} counts, with their 11 millisecond half-life, to be sure that the counts came from N^{12}. It is a simple matter to subtract in real time, any relatively constant background (and almost all radioactive substances except N^{12} do not decay appreciably in 44 milliseconds). The basic idea is that one registers two counts (1) the total number in the full 4 half lives of N^{12}, and (2) the number in the fourth half-life of N^{12}. We then multiply this last number by 4, and subtract the product from (1). That provides strong discrimination against gamma ray emitters with lifetimes greater than 0.5 seconds. (This is the "real time subtraction technique" referred to earlier.) I have checked this method, analytically, over a wide range of background half lives, and background counting rates, and it operates very satisfactorily. If the background counting rate is small compared to the N^{12} initial counting rate, the "subtracted number of counts" is 69% of the real number of N^{12} counts. (See Fig. 2.) At higher background rates, the subtracted number is closer to the real number, but if the background is too high, statistical fluctuations cause

problems. It is for this reason that I have devoted so much attention to reducing the various kinds of backgrounds.

But now that I have been unsuccessful in finding a serious source of background counts in the 4.4 MeV energy range, except for the N^{16} discussed earlier, it may be that the background subtraction routine just described is not a good use of the full 44 milliseconds. I believe it may be more useful to confine the measurements to a single half-life (11 milliseconds), and use the four times more rapid scan mode to accomplish one of two important objectives. We can speed up the belt, by a factor of four, to examine each bag in 1.5 seconds, instead of 6 seconds. That would permit 2400 bags to be screened every hour, instead of 600. Or, equally easily, we could scan each bag with pixels only 1.25 inches on a side, at the 6 seconds per bag rate. I believe the faster belt speed is the preferable choice, and I will explore that option in some detail, to the point that anyone interested in the higher resolution mode will know what to do to avoid the "smearing" of the image, caused by counting for only one half-life, instead of 4.

Suppose we are examining a bag with no nitrogen in it except for a 2.5-inch cube of nylon. If we look at the gamma ray counter, after each pixel is scanned at the rate of one pixel per 11 milliseconds, we will find it reads zero for every pixel scanned up to the one containing the nylon. That pixel will show n counts, but the next pixels, all of which contain no nitrogen, will show counts of n/2, n/4, n/8, n/16, etc., respectively, because of the decay of the N^{12}. This "smearing of the image" can quite easily be eliminated, in real time, by the following simple algorithm:

As the x-ray beam scans the bag from the first to the Nth pixel, the number of counts registered by the scintillator in the mth 11 millisecond interval, n_m

is added to the number in the mth memory register. If that is all that happened, we know that there would be a "decay tail" extending upward through the registers labeled m+1, m+2, m+3, etc. To get rid of that tail, we instruct the computer to add n_m to the mth register, and subtract $n_m/2$ from the m+1 register, $n_m/4$ from the m+2 register, etc. It is obvious that for the simple case just discussed, when there was a nylon cube in an otherwise evacuated bag, all the expected $2n_m$ counts end up in the correct register, labeled m. (Registers beyond m will, at first, have negative numbers of counts in them, and will be filled up to zero, due to the decay of the N^{12} atoms in pixel m.) It can easily be seen that if we don't operate on the counts coming from the counter, but on those remaining in the corresponding register, this algorithm will "desmear" any image to look like the one that would have been obtained from that bag if each pixel had been counted for 10 half lives instead of only 1. And as said earlier, we can operate with 1.25-inch pixels, using the same "desmearing algorithm," at the rate of 1 bag every 6 seconds (instead of the 1.5 seconds used in the last illustration). There may be some problems with the spread of the x-ray beam, in going down to 1.25-inch pixels, but I think it can be done successfully. (Tests will show whether or not a practical nitrogen detector can operate at 1.5 seconds per bag, rather than at the 6 seconds per bag rate, which is the method that seems sure to avoid background interferences. I mention the faster method only as a possibility that has some fine advantages, in the event that background problems cause less of a problem that my "worst case scenario" suggests.)

I should finally calculate the radiation dose to materials in the bag, due, first of all to the x-rays, and secondly, due to the radioactivity of such isotopes as C^{11} and O^{15}. Rough estimates of these two doses includes 250 rads for the x-ray dose, and 0.1 rads from

the radioactivity. These numbers indicate that film will be exposed, if left in checked baggage. But that presents no real problem, since most people who use film are frankly skeptical of notices that say film will not be exposed by the existing x-ray scanners, so they carry their film, to bypass the x-ray beams. It is believed professional photographers (and most amateurs) who carry their film around the x-ray machines now in use, will not be seriously inconvenienced to do the same with the N^{12} scanners; in fact, there will be signs posted warning them to do so.

One might wonder if it could be possible to shield three pounds of explosive with enough absorbing material, such as lead, to keep the high energy x-rays from hitting the nitrogen, and therefore stopping the reaction, $N^{14}(gamma,2n)N^{12}$, or for the same reason, to keep the 4.4 MeV gamma rays from the explosive, from reaching the detector. The answer to both questions is no; the shield would weigh close to one hundred pounds, even if the explosive were in its most compact form of a sphere, and considerably more, for more ordinary shapes. The reason is that the attenuation length in lead for 4.4 MeV gamma rays is about 58 grams per cm^2, and about 4.5 times less for 50 MeV x-rays. So I see no way in which the proposed technique for finding nitrogen can be countered either by shielding the explosive, or by including some harmless material in the bag that would "jam" the detector, with too high a counting rate of high energy delayed gamma rays from a very short-lived radioactive isotope. There doesn't seem to be any such material in the whole periodic table.

The next paragraphs will describe some of the unusual features of hollow scintillation detectors for 4.4 MeV gamma rays. There are not many demands for counting gamma rays in this energy range, and when there are, they are usually met by the use of solid scintillating material of the sodium iodide or bismuth germinate

variety, which have components of high atomic number, that absorb high energy gamma rays more readily than do materials of lower atomic number. This situation does not occur when half million electron volt gamma rays are detected. Such "medium energy" radiation is absorbed almost equally well by all elements, on a gram per square centimeter basis. So it is interesting to note that for low energy gamma rays (e.g. 100 keV), and for high energy gamma rays (e.g. 4.4 MeV) lead is a very much more powerful absorber than light elements (e.g. carbon), on a mass per unit area basis, but for medium energy radiation, all elements--except hydrogen--are very nearly equally good absorbers. (Surprisingly, hydrogen is nearly twice as good as most every other element, but its density is so low that no one would seriously consider its use as a gamma ray absorber.)

Sodium iodide and bismuth germinate are excellent substances to use in detectors for 4.4 MeV gamma rays, but for use in the proposed nitrogen detectors, they have two serious disadvantages, (1) they are very expensive in sizes large enough to surround a "standard bag," and (2) their maximum counting rates are very low compared to what can easily be tolerated in organic scintillators, in either liquid or solid form. The pulses from the high Z, expensive scintillators have a characteristic time width of 1 microsecond, in contrast to the characteristic time width for organic scintillators, which is shorter by 2 or 3 orders of magnitude. So for both of these reasons we will use organic scintillators in the proposed nitrogen detector, in two different detector geometries that have great promise, and that will be described later. Organic solids are of course now commonly used, but because they are made of all low Z elements, they are not very efficient absorbers of 4.4 MeV gamma rays. To make organic scintillators more efficient, it would be convenient to use liquids that have been "doped" by the addition of high

Z material, in solution. Such doped scintillators have been used in past years. The Bichron Company of Newbury, Ohio can supply a liquid organic scintillator that was doped with 30% by weight of Tin Oxalate, so that its absorption length for 4.4 MeV gamma rays was considerably less than that for undoped liquid scintillator.

Modern environmental protection laws now prohibit the use of such high Z dopants; they are all classed as poisons. So I had to devise alternative schemes for detecting 4.4 MeV gamma rays, both of which I will now describe. But if a non-poisonous high Z additive should become available, it would be preferred over either of the two alternative detectors, each of which can do an effective job of detecting the 4.4 MeV gamma rays, and rejecting annihilation radiation, and other medium energy delayed photons.)

To understand the proposed sandwich detector for 4.4 MeV gamma rays, we must examine the way such gamma rays are absorbed in lead, and how the resulting pair (of an electron and positron) loses its energy in the plastic scintillator, and how the scintillation light is "piped" to the photomultiplier(s).

High energy gamma rays are absorbed primarily by creating an electron-positron pair (this is called "materialization," or "working the Einstein $E=mc^2$ equation backwards," where we use energy--of the gamma ray--to create the mass of two electrons, which takes 1.022 MeV). Each electron of the pair moves nearly in the direction of the gamma ray, which disappears in the process. The sum of the kinetic energies of the two electrons (+ and -) is equal to the gamma ray energy minus 1.022 MeV. When the positron stops, it gives rise to two annihilation photons, each with an energy of 0.511 MeV, as is well known. So overall, energy is conserved; our 4.4 MeV photon gives rise to about 3.4 MeV of kinetic energy, shared by the electron and

positron, and when the positron annihilates, the "missing" 1 MeV is released.

The cross-section for the pair-production absorption process, at any particular gamma ray energy, is proportional to Z^2, and since atomic weights increase roughly proportional to Z, the mass absorption coefficient (measured in cm^2/gm) increases roughly as Z. So to get the most absorption in a given thickness of material (measured in gm/cm^2), we naturally use lead (density = 11.3 gm/cm^2 and Z = 82) as the absorber. The mass absorption coefficient of lead, for 4.4 MeV gamma rays, is close to 0.017 cm^2/gm. So if we want to reduce the gamma ray intensity to e^{-1} (=0.368), we must use $(0.017)^{-1}$ = 58 gm/cm^2 of Pb, = 5.13 cm thickness. That would be fine if all we wanted to do was absorb the gamma rays.

But we need to absorb the created electron pair in scintillating material, and register the optical photons in photomultipliers. So we must know how electrons are absorbed in both lead and organic scintillating material. The rule of thumb for the latter is that a high energy electron (kinetic energy greater than its "rest energy" of 0.511 MeV) loses about 2 MeV per gram per cm^2 of low Z materials, and less than that for heavier elements. (For Pb, the energy loss is about 1.3 MeV per gm/cm^2.) This number tells us that the lead must be thin, if we want to make sure that the electrons emerge, to be largely absorbed in the plastic scintillator. If we used 1 mm thick Pb plates (ρx = 1.13 gm/cm^2), each electron could lose 1.13 x 1.3 MeV = 1.47 MeV for a total "invisible energy" of 2 x 1.47 = 2.94 MeV. So, with 4.4 MeV of original gamma ray energy, we could have lost 1.022 MeV + 2.94 MeV, to end up with only 0.44 MeV absorbed in the scintillator.

This is the same energy an electron pair could have if it were made "at the far side" of the Pb plate, under the influence of a 1.46 MeV gamma ray (in a pair

production process), or under the influence of an annihilation photon (in a Compton scattering process). This would certainly not give adequate energy resolution. So we must use thinner Pb, to make more of the kinetic energy of the electron pair appear in the plastic scintillator. But when we make the Pb thinner, we need more sheets to accomplish our other important objective of absorbing the gamma rays, and that means we must have more layers of plastic scintillator, thus increasing the overall thickness and the complexity of the detector. (This example will show why the use of a "high Z-doped" liquid scintillator would have been so much more satisfactory; in such material, we do not "lose" the electron energy in the gamma ray-absorbing material--it is transparent to optical photons, and not opaque, as lead is.)

We have seen that 1 mm sheets of Pb are too thick, as far as their electron-absorbing properties are concerned. We will now look at those same sheets, from the point of view of their gamma ray absorbing properties. If our stack consisting of Pb and plastic scintillator consisted of 1 cm thick plastic interleaved with 1 mm Pb sheets, for a "unit thickness" of 1.1 cm, and if the total thickness was 30 cm (=1 foot), there would be 30/1.1 = 27 layers or 1.13 x 27 = 30.8 gm/cm^2 of Pb. This would absorb 1-exp (-30.8/58) = 41% of the gamma rays, which would be quite a satisfactory value.

If we cut the Pb thickness in half, to 0.5 mm, our maximum electron energy loss drops to 1.47 MeV, which is probably tolerable, but can be made smaller if we need better energy resolution in our gamma ray detector. If we use 0.5 mm Pb sheets, and still a 1 foot thick sandwich, we will detect 23% of the gamma rays, which is not too far from the 1/4 I assum d in calculating the expected counting rates.

A representative detector element is illustrated schematically in Figs 3A and 3B. It will be understood that this element is representative of elements A and C, or either of the elements B and D. Sheets plastic scintillator 101 are placed between sheets of lead foil 102. Light is discharged to two reflection chambers 103, 104. Light is counted from the reflection chamber by photomultiplier 107.

The numerical examples I've given in this section will show that a reasonable compromise can be made between the conflicting requirements of gamma ray attenuation and gamma ray energy resolution. Referring to Fig. 3A and 3B, the thickness of the plastic scintillator 101 should probably be cut from 1 cm to 0.5 cm, because 1 cm can absorb 4 MeV from a pair of electrons, which is more than is available. So we can use more layers of lead 102, and so gain in gamma ray absorption.

I will now describe briefly the light-piping properties of plastic scintillator, using the phenomenon of total internal reflection. It is standard practice in high energy physics laboratories, worldwide, to pass high energy particles normally through plastic scintillators, for timing measurements. (The energy lost in the plastic is usually not measured, since it is very nearly the same for all the singly-charged particles of interest.) The scintillation photons are emitted uniformly in all directions, so the fraction emitted outside a cone with half-angle (about the normal to the surface) equal to $\sin^{-1} n^{-1}$ will be totally internally reflected from their point of origin all the way to a photomultiplier. (Certain restrictions are placed on the cross-sections of the "light pipes" from the scintillator to the photomultiplier, but these restrictions are well understood by practitioners of this art, so it is sufficient to state that one can do satisfactory pulse-height analysis on the light pulses from gamma

rays, particularly if one uses a photomultiplier on both sides of each scintillator.

It is also well known in this art that one can cut down on the required number of photomultipliers by using secondary fluorescent light pipes. But for the present purpose, it is sufficient to say that layered detectors of the kind described above can be obtained from commercial suppliers, and they should be able to satisfy the primary requirements of counting 4.4 MeV gamma rays with acceptable efficiency, and rejecting most gamma rays with energies below some value in the 1 to 1.5 MeV range, and above 5.5 MeV, although the latter cut-off is not so important.

The other detection scheme applicable to the proposed nitrogen detector makes use of undoped organic liquid scintillator, and utilizes the Compton process instead of the pair-production process, as the mechanism of interaction between the 4.4 MeV gamma rays and the condensed matter in the detector. It turns out that the Compton cross-section in organic scintillator is larger than the pair-production cross-section in lead, so one might wonder why my first modified detector used lead. The answer is simply that in pair-production, the incoming photon disappears, so all pairs share the same total kinetic energy of $E=2mc^2$. That is ideal in a doped scintillator, but when we go to the sandwich detector, we see that the visible energy in each pair depends on which side of the Pb sheet the pair is created. So we have lost the beautiful property that is inherent in the pair-production process, of equal sized pulses in the photomultiplier for all equivalent photons. So it is then worth looking more carefully at the Compton process, where there is an inherent variation in pulse height, for a given incoming energy, depending on how the photon scatters at each interaction. The total Compton interaction length in liquid scintillator is about 1 foot, so one can make an acceptable, and very

inexpensive energy sensitive detector for 4.4 MeV gamma rays, with no high Z dopants, and no lead foils. (In fact, there is such a detector in my laboratory, on which I did the basic design, which has a thickness of 14 inches of liquid scintillator in all directions about a source of gamma rays--solid angle = 99 + % of the total possible). So, such a detector was my first choice when the doped scintillator disappeared as an immediate possibility, because I knew its properties in great detail. I then explored the sandwich detector because it was in effect a solid doped detector. But the necessary "smearing" of the energy resolution described above made me realize that the "pure Compton" detector should not be discarded simply because it had an inherent energy smeared response. So I now believe that experiments will have to be done to determine which of these two detectors is to be preferred. For that reason, my claims will describe both kinds, and I am confident that both can do the job.

In earlier sections of this descriptive matter, I stressed the need to suppress the sensitivity of the gamma ray detector to photons with energies below some "cut-off value," such as 1 to 1.5 MeV. The more I have examined possible background gamma rays, the less I find in value about the high energy cut-off. The only possible interfering gamma ray in that energy range is the 6 MeV photon from N^{16}. But as I've shown earlier, such a gamma ray is largely eliminated from consideration by the fact that its half-life is 700 times longer than that of N^{12}. So I now think there is a very good chance that we can operate the gamma ray detector without any particular high energy cut-off, depending mainly on the subtraction technique to eliminate any effects due to N^{16}, with its much longer half-life. (Of course we will cut out the very large pulses from cosmic rays, which will typically amount to an energy loss in the detector of more than 100 MeV.)

The reader will understand that this invention extends to any method of detecting the reaction of $^{14}N(\gamma,2n)^{12}N$. It is the uniqueness of the decay above 1 MeV in 2% of these reactions which gives the desired signature which I detect for the overabundance of nitrogen.

The reader will also note that I do not prefer to have sufficient energy present to cause the reaction of oxygen to either ^{12}N or ^{13}O. These limitations will be understood only to avoid the resultant decays from these reactions from interfering with the detectability of the reaction $^{14}N(\gamma,2n)^{12}N$. Narcotics are sometimes smuggled in checked baggage. All such narcotics are ~4% nitrogen by weight. To see if we can detect cocaine we take a single standard 8" x 5" x 3" kilogram brick lying flat in the bag. A pixel contains (40.32 cm^2) (7.62 cm) (½ gm/cm^3) ~ 153.6 gm of cocaine with a nitrogen surface density of (153.6/40.32) (0.04) ~ 0.153 gm/cm^2. There will be 0.01 $moles^N/cm^2$ ~6.6×10^{21} $atoms^N/cm^2$. The detected signal will be (6.6×10^{21}) $(10^{-28})(4.4 \times 10^{11})(.02)(.04)$ - 230 counts/pixel on average spread over only 6 to 10 pixels. This is five times the atmospheric nitrogen rate. Therefore, we will be able to detect this distinctive profile with our position specific sensitivity.

The reader will understand that many narcotics are smuggled in the form of bricks or other distinctive shapes. The discovery of a profile of such shapes will naturally assist those observing the detector of this invention in locating bags having a high probability of contained narcotics.

Most commonly used narcotics have ranges of nitrogen varying from 3% to 6%. It will be apparent that the apparatus herein disclosed will be effective in locating such narcotics concealed within luggage G.

This completes the description of the nitrogen-detecting technology.

WHAT IS CLAIMED IS:

1. A method of scanning a series of articles for randomly placed nitrogen concentrations comprising the steps of:

providing an x-ray source having sufficient photons in the energy range sufficient to cause a significant reaction

$^{14}N(gamma,2n)^{12}N$

but insufficient to cause a significant reaction of ^{16}O to ^{12}N or to ^{13}O;

irradiating a suspect article to determine the presence of nitrogen with radiation sufficient to cause the reaction $^{14}N(gamma,2n)^{12}N$ where gamma is x-radiation and n is a neutron;

detecting gamma radiation from said suspect article in a detector with energy exceeding 1.0 MeV.

2. The method of claim 1 and wherein said detecting steps includes suppressing gamma radiation signals below 2 MeV.

3. The method of claim 1 and wherein said detecting step includes the steps of suppressing radiation below 2 MeV and suppressing gamma radiation above 6 MeV.

4. The method of claim 1 and wherein said irradiating a suspect article step includes conveying said suspect article relative to an irradiating source.

5. The method of claim 4 and wherein said article is conveyed at 0.5 ft/sec.

6. The method of claim 1 and wh rein said irradiating step includes irradiating an article in discrete pixels.

7. The method of claim 1 and wherein said d tecting step includes detecting for said radiation over a solid angle up to but not exceeding 90%.

8. The method of of claim 6 and wherein said detecting step includes detecting each scanned discrete pixel for approximately four half lives.

9. The method of claim 6 and wherein said detecting step includes detecting each scanned discrete pixel for approximately one half-life, and removing the otherwise confusing smear of the image.

10. The method of claim 1 wherein said scanned article is luggage and including prior to said irradiating steps the steps of placing luggage in a gas containing substances other than the nitrogen and varying the atmospheric pressure on said luggage whereby atmosphere containing nitrogen is substantially flushed from said luggage.

11. The invention of claim 1 and wherein said detecting step is alternated with said irradiating step whereby said irradiating energy is not detected.

12. The method of claim 6 and wherein said detecting step includes accumulating counts from a detector in a memory after irradiating a pixel and subtracting one-half of a previous count from a subsequently to be scanned pixel whereby traces of half lives are removed.

13. A method of scanning a series of conveyed articles for randomly placed nitrogen concentrations comprising the steps of:

providing an x-ray source having sufficient x-rays in the range sufficient to cause a significant reaction

$^{14}N(gamma,2n)^{12}N$

but insignificant to cause a significant reaction ^{16}O to ^{12}N, or ^{16}O to ^{13}O;

irradiating a relatively moving suspect article to determine the presence of nitrogen with radiation sufficient to cause the reaction $^{14}N(gamma, 2n)^{12}N$ where gamma is x-radiation, and n is a neutron;

detecting delayed radiation in a scintillation detector in the range exceeding 1 MeV for a plurality of half lives of the decay of said N^{12}; and

making a first count of said scintillation detection for a plurality of m half lives of said N^{12} and making a second count of said scintillation detector for a residual half-life of N^{12}; and

multiplying the counts in the last half-life by m, and subtracting those multiplied counts from the first count, to give a nitrogen response largely free of counts from any longer-lived background radioactivity.

14. Apparatus for scanning a series of relatively moving articles for randomly placed nitrogen concentrations said apparatus comprising:

an x-ray source having sufficient photons in the energy range sufficient to cause a significant reaction

$^{14}N(gamma,2n)^{12}N$

but insufficient to produce a reaction ^{16}O to ^{12}N, or ^{16}O to ^{13}O;

means for scanning said x-ray source on a suspect article to determine the presence of nitrogen with radiation sufficient to cause a reaction $^{14}N(gamma,2n)^{12}N$ where gamma is x-radiation and n is a neutron; and

a detector located adjacent said article for detecting gamma radiation above 1.0 MeV.

15. The apparatus of claim 14 and including:

a tunnel in the earth;

a conveyor passing through said tunnel in the earth; and

said detectors are mounted in said tunnel in the earth.

16. The apparatus of claim 14 and including a liquid target for said radiation on the opposite side of said belt for absorbing said x-ray radiation.

17. The invention of claim 14 and wherein said tunnel is lined with material selected from the group comprising boron oxide, sulfur and lead.

18. The invention of claim 14 and including means for placing said article in a bath of gas other than nitrogen and fluctuating the pressure on said article to flush ambient nitrogen from said article.

19. The invention of claim 14 wherein said radiation source overlies said tunnel.

20. The invention of claim 14 wherein said detector contains a liquid scintillator.

21. The invention of claim 20 and wherein said detector contains a liquid scintillator having a high Z dopant.

22. The invention of claim 14 and wherein said detector contains sandwiched plastic scintillator and sheets of lead.

23. The method of claim I and where said nitrogen is contained in explosiv .

24. The method of claim I and where said nitrogen is contained in narcotics at a level of at least 3% by weight.

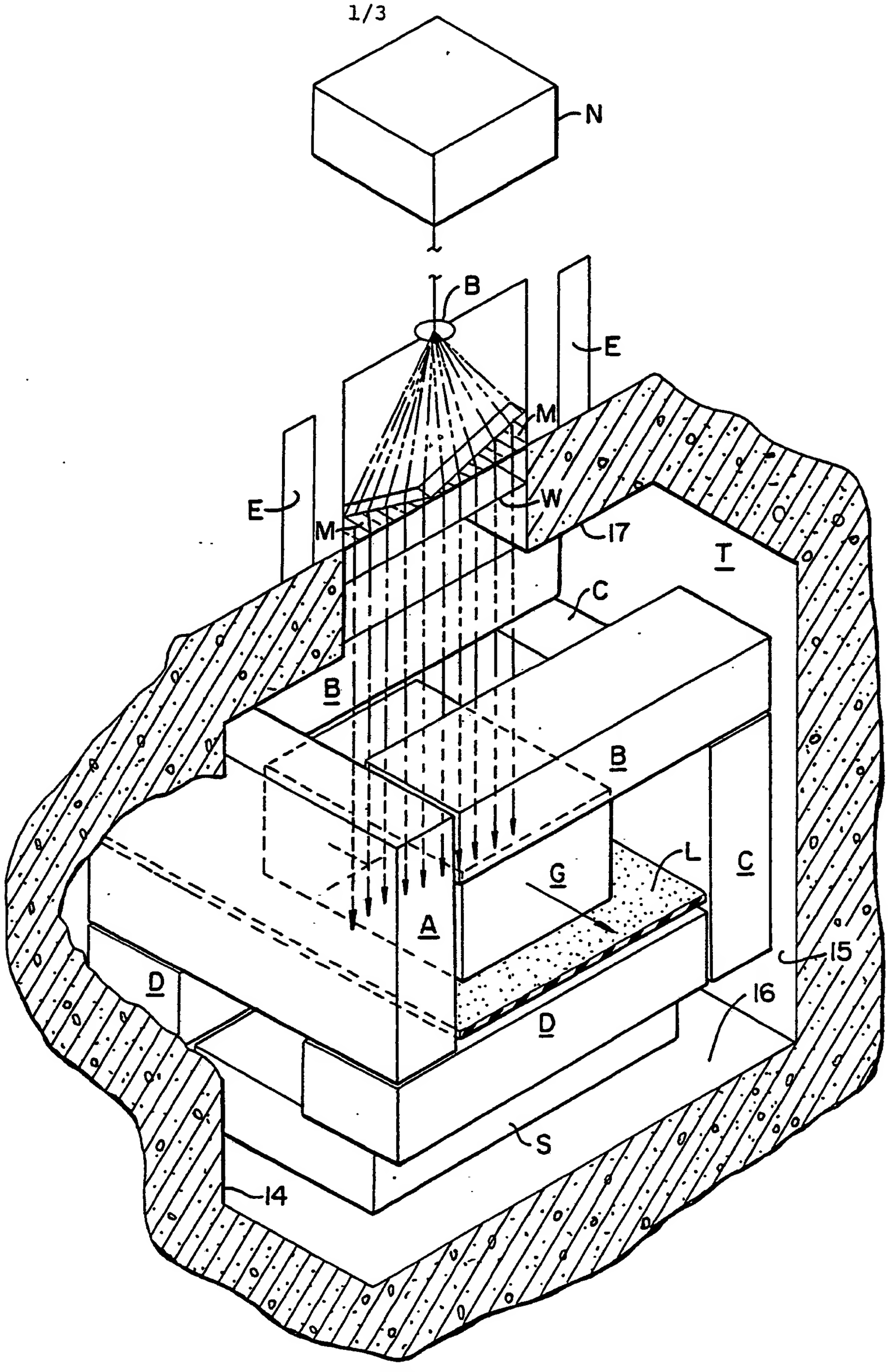

FIG._1.

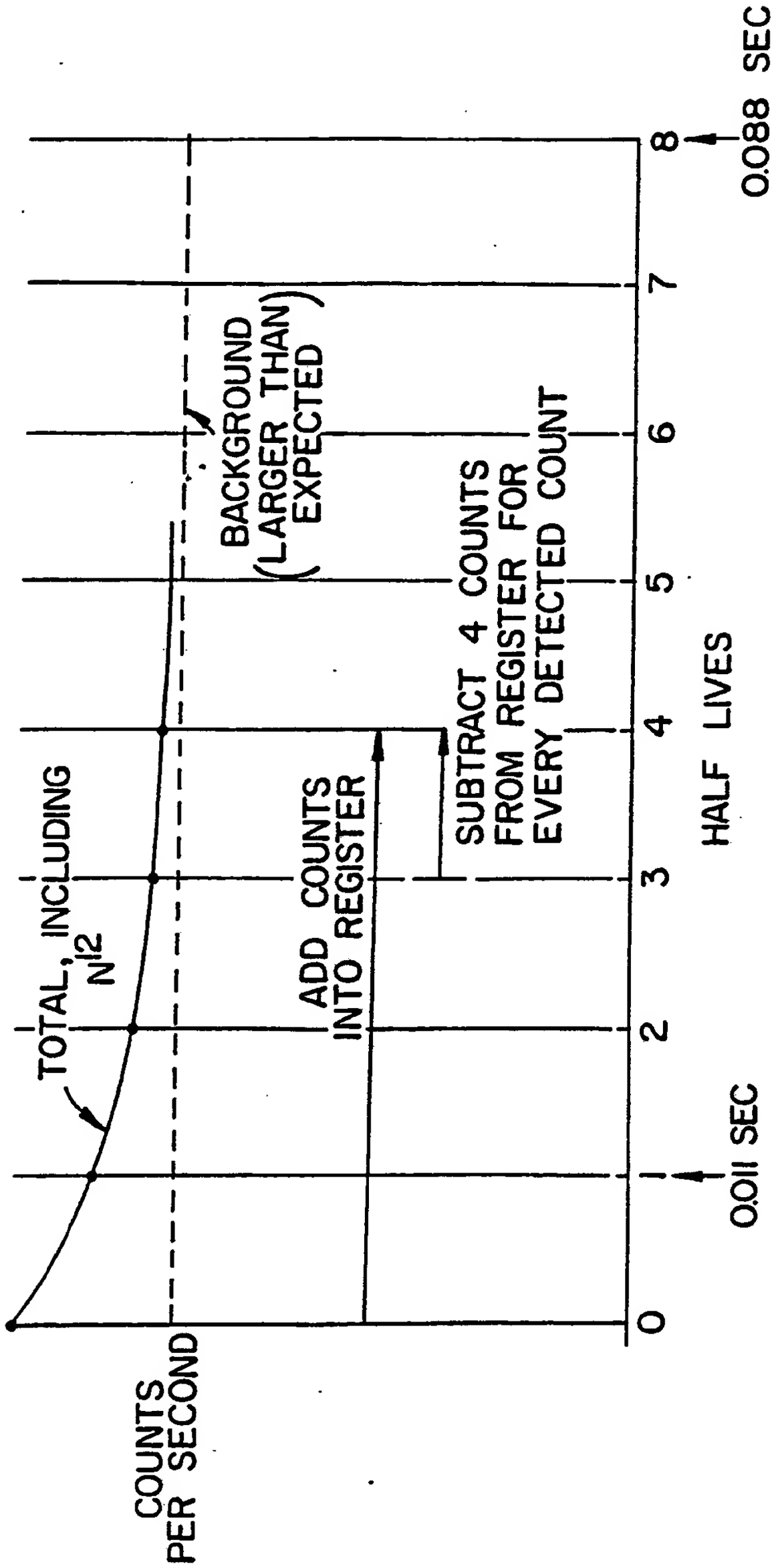
COUNTS PER SECOND
TOTAL, INCLUDING BACKGROUND (LARGER THAN EXPECTED)
N12
ADD COUNTS INTO REGISTER
SUBTRACT 4 COUNTS FROM REGISTER FOR EVERY DETECTED COUNT
HALF LIVES
0.011 SEC
0.088 SEC
0
2
3
4
5
6
7
8

FIG_2.

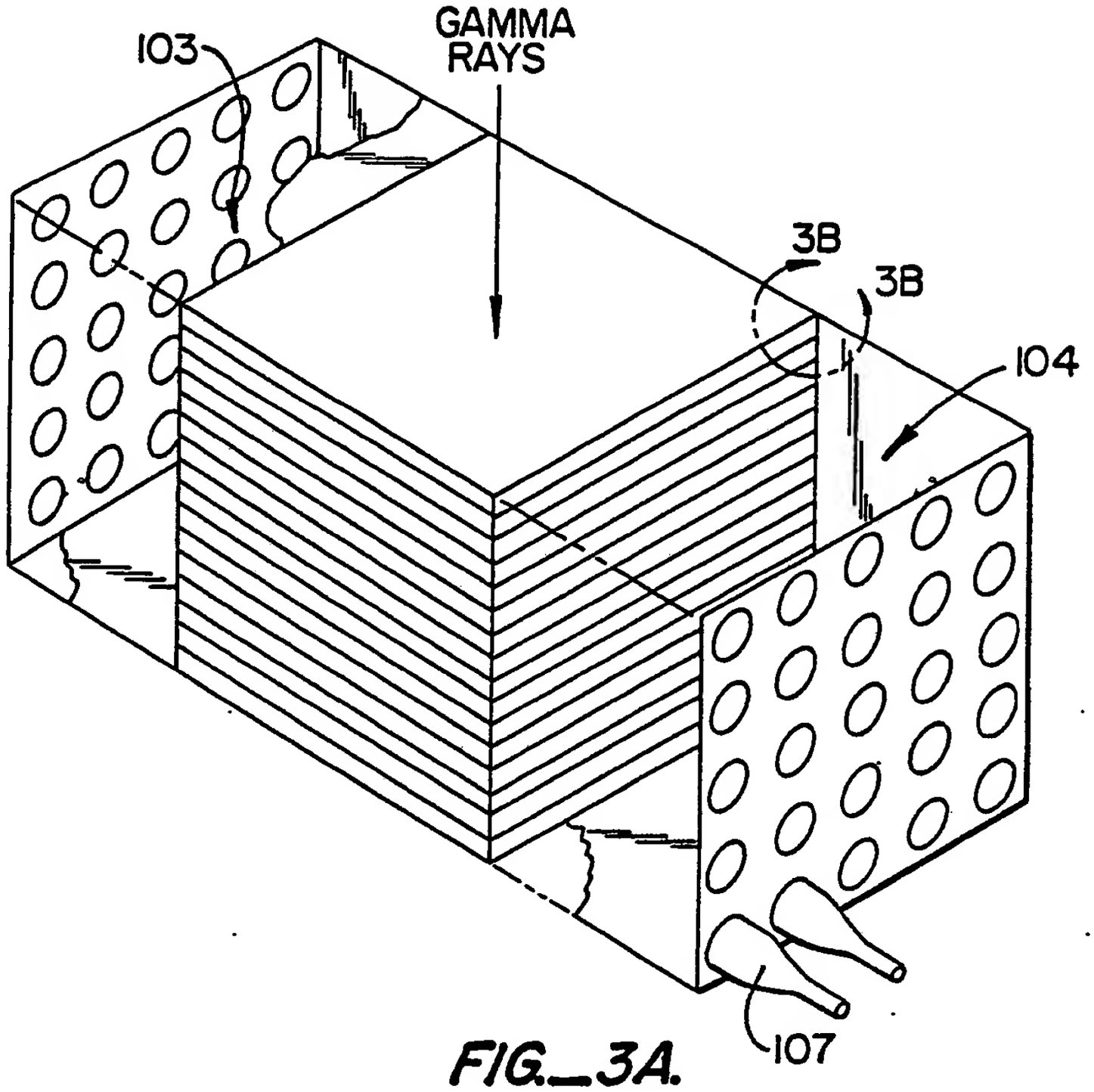

FIG._3A.

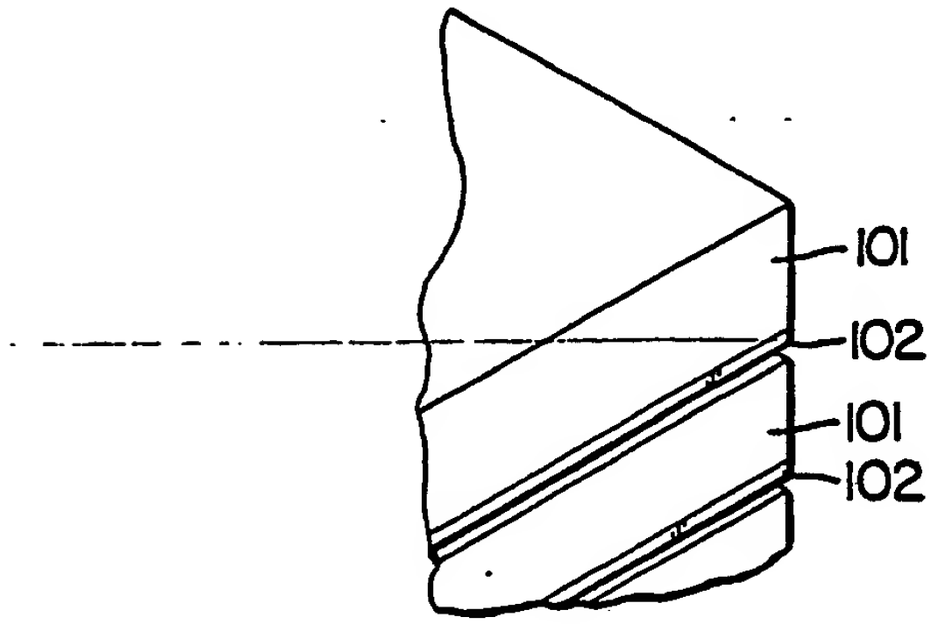

FIG._3B.

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 87/02170

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ³

According to International Patent Classification (IPC) or to both National Classification and IPC

INT. CL. G21G 1/12; G21K 5/10
U.S. CL. 376/157

II. FIELDS SEARCHED

Minimum Documentation Searched ⁴

Classification System ⁵	Classification Symbols
U.S.	376/157, 159

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched ⁶

III. DOCUMENTS CONSIDERED TO BE RELEVANT ¹⁴

Category ⁷	Citation of Document, ¹⁶ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁸
Y	US, A, 3,662,882 Published 16 May 1972, Obermayer.	1-24
Y	US, A, 4,031,388 Published 21 June 1977, Morita et al.	1-24
Y	US, A, 3,832,545 Published 27 Aug. 1974; Bartko.	20-22
A	US, A, 4,251,726 Published 17 Feb. 1981, Alvarez.	1-24
A	US, A, 4,428,902 Published 31 Jan. 1984, Murray.	1-24
A	US, A, 3,997,787 Published 14 Dec. 1976, Fearon et al.	1-24
A	N, Radiochem. Radioanal. Letters, Vol. 5, 1970, See pages 217-222, Kapitza et al.	1-24

* Special categories of cited documents: ¹⁵

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search ²

04 December 1987

Date of Mailing of this International Search Report ²

18 DEC 1987

International Searching Authority ¹

ISA/US

Signature of Authorized Officer ¹⁰

Harvey E. Behrend

Form PCT/ISA/210 (second sheet) (May 1986)

FURTHER INFORMATION CONTINUED FROM THE SEC NO SHEET

A	N, Journel of Radioanalytical Chemistry, Vol. 36, No. 1, 1977, See pages 221-238, Sato et al.	1-24
A	N, Nucleonics, September, 1965, Vol. 23, No. 9, Tilbury et al., See pages 70-78 (particularly page 71).	1-24
A	US, A, 3,124,679, Published 10 March 1964, Tittman et al., See col. 2, lines 59+	1-24

V.☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [1]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1.☐ Claim numbers . because they relate to subject matter [2] not required to be searched by this Authority, namely:

2.☐ Claim numbers , because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [3], specifically:

VI.☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [1]

This International Searching Authority found multiple inventions in this international application as follows:

1.☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2.☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3.☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4.☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.